

# Relation of inversely graded deposits to suspended-sediment grain-size evolution during the 1996 flood experiment in Grand Canyon

David M. Rubin

U.S. Geological Survey, M.S. 999, Menlo Park, California 94025

Jonathan M. Nelson

David J. Topping

U.S. Geological Survey, M.S. 413, Lakewood, Colorado 80225

## ABSTRACT

Before Glen Canyon Dam was completed upstream from Grand Canyon, floods scoured sand from the channel bed and deposited sand on bars within recirculating eddies. After completion of Glen Canyon Dam in 1963, peak discharge of the mean annual floods dropped from about 2600 to 900 m<sup>3</sup>/s, and 85% of the sediment supply was eliminated. Under the postdam flow regime, sand bars in eddies have degraded. In an experiment to study, in part, the effects of floods in rebuilding these bars, a controlled flood was released from Glen Canyon Dam in late March and early April 1996. Although fluvial sequences characteristically fine upward, the deposits of the experimental flood systematically coarsen upward. Measurements of suspended-sediment concentration and grain size and of bed-material grain size suggest that the upward coarsening results from the channel becoming relatively depleted of fine-grained sediment during the seven days of the high-flow experiment. Predam flood beds of the Colorado River also coarsen upward, indicating that supply-limitation and grain-size evolution are natural processes that do not require the presence of a dam.

## INTRODUCTION

### Background

Water in the Colorado River passes through Glen Canyon Dam before flowing through the 400 km length of Grand Canyon. Until Glen Canyon Dam was completed in 1963, the Colorado River in Grand Canyon had a mean peak annual discharge of 2600 m<sup>3</sup>/s, and carried a mean annual sediment load of  $3 \times 10^7$  m<sup>3</sup> (Andrews, 1990); discharge ranged from as little as 28 m<sup>3</sup>/s (1000 cfs) to more than 3400 m<sup>3</sup>/s (120 000 cfs) over the course of a year. The dam drastically reduced these annual discharge fluctuations, but introduced daily fluctuations (in the extreme case having daily minima as low as 28 m<sup>3</sup>/s [1000 cfs] and maxima as great as 850 m<sup>3</sup>/s [30 000 cfs]) to meet electrical power demands. Virtually all sediment coming down the river was cut off by the dam, and sediment was supplied to the postdam river only from tributaries downstream from the dam (chiefly the Paria and Little Colorado Rivers); ~15% and 10% of the predam total sediment and sand loads, respectively, were supplied by these sources.

As a result of the new flow regime and greatly reduced sediment supply, sand bars in the canyon began eroding, necessitating research to determine whether a new operating scheme for the dam could mitigate this degradation. This paper presents selected results from research conducted during a week-long experimental flood released from Glen Canyon Dam during March–April 1996 (Collier et al., 1997). This experiment was designed, in part, to test the hypothesis that new sand bars could be built in Grand Canyon—

despite the reduced postdam (10% of predam) supply of sand—by transporting sand from the channel bed to channel-margin bars. The hydrograph of the experimental flood consisted of a rapid increase in discharge from 238 m<sup>3</sup>/s (8400 cfs) to 1290 m<sup>3</sup>/s (45 400 cfs) over 5.75 hr, followed by seven days of constant discharge at 1290 m<sup>3</sup>/s, and then a slow decrease over 3.2 days to 238 m<sup>3</sup>/s.

### Supply Limitation

Sand bars in the Colorado River in Grand Canyon form in recirculating eddies in lateral separation zones (Schmidt and Graf, 1990; Rubin et al., 1990). The formation and morphology of these eddy deposits are controlled by main-channel sediment supply and by eddy hydraulics and geometry. Because of the dependence on sediment supply, understanding and predicting the flow structure in lateral separation eddies is insufficient for predicting deposition or erosion in eddy flows; main-channel sediment supply is at least as important as flow patterns. For identical flows, an eddy deposit can either aggrade or erode, depending on the concentration of sediment in the main-channel flow. In rivers where the main-channel sediment transport is uniquely determined by flow discharge, the dependence of eddy deposit morphology on main-channel transport can be parameterized in a straightforward manner; this is not the case in Grand Canyon.

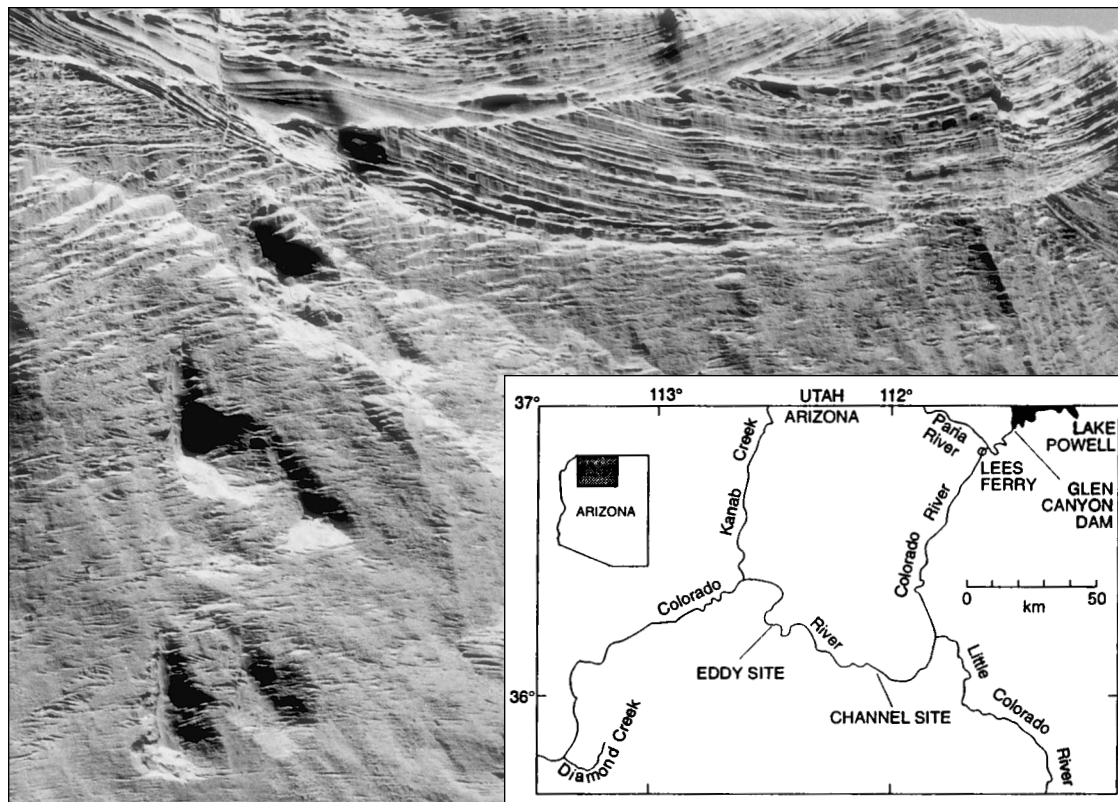
The Colorado River in Grand Canyon is currently and historically a supply-limited system, with respect to both sand and finer material; we define “supply-limited” to mean that the flow

transports less of certain grain sizes than it would if more sediment of those sizes were available. Historically, sediment concentration in Grand Canyon decreased through time during spring snowmelt floods, reflecting this supply limitation, as explored in the classic paper by Leopold and Maddock (1953) in which the sediment rating-curve hysteresis at this site was described.

Supply limitation is particularly evident in Grand Canyon because sediment-supplying events are typically not synchronous with periods of high flows. This situation is characteristic of both predam and postdam conditions, although for somewhat different reasons. Prior to the construction of the dam, the majority of high flows occurred during annual snowmelt periods, and the majority of sediment was supplied to and stored in the channel during the monsoon season in late summer and early fall. Likewise, in the postdam period, sediment-transporting flows do not occur simultaneously with sediment-supplying events. Tributary sediment is still added locally during the monsoon season, but high main-channel sediment transport occurs when discharge is increased to meet power-generation needs or to adjust reservoir levels.

Because of the mismatch in timing of tributary sediment supply and main-channel sediment transport, the concentration and grain size of suspended sediment and the associated bed material evolve during the year (finer grain size and higher sand transport for a given discharge immediately after sediment is introduced, and coarser grain size and lower transport after high-flow events have winnowed the bed). In the predam period

Figure 1. Flood deposit at eddy site. Photo was taken after recession of flood and shows upper 1.5 m of a 5-m-thick deposit. Lower left shows finer-grained climbing-ripple structures (ripple foresets dip toward the right), whereas top 0.5 m shows coarser crossbedded strata. Inset shows study sites.



this typically occurred over the time scale of weeks or months, but in the postdam era (with reduced sediment supply) this adjustment may occur over a few days of high flow.

## FIELD OBSERVATIONS

### Coarsening-Upward Deposits

Sediment deposited during the 1996 flood experiment was examined in trenches on several dozen eddy bars (Fig. 1) and was sampled vertically at five of these sites. The mean grain size coarsens upward by roughly a factor of two, from 0.06–0.10 mm at the base to 0.10–0.19 mm at the top of the deposits (Fig. 2). The increase in mean grain size occurs not merely by the removal of fines, but also by an increase in the modal size and an increase in size of the coarsest fraction. In the field, the upward coarsening is great enough to be visible to the eye. Most of the flood deposits are composed of climbing-ripple deposits, but at some locations the finer-grained climbing-ripple structures are confined to the basal deposit and are overlain by coarser-grained crossbedding (Fig. 1). Predam deposits also coarsen upward (Fig. 2).

### Sediment Concentration and Grain Size

To study the connection between eddy deposits and main-channel sediment transport, we monitored bed and suspended sediment during the flood experiment at two sites, one in the main channel at the “near Grand Canyon, AZ gage station number 09402500” and one in an eddy located 55 km downstream (Fig. 1). At the main

channel site, suspended-sediment samples were collected from the U.S. Geological Survey cableway using both a P-61 point sampler and a bag sampler with a D-77 head. The P-61 sampler was deployed at two verticals located at one-third and two-thirds of the channel width following both a point-sampling and depth-integrating methodology. In the point-sampling methodology, three samples were collected at six points in each verti-

cal on three days during the seven-day flood. In the depth-integrating methodology, two to four samples were collected at each vertical on each day of the flood. The D-77 sampler was used to collect cross-sectionally averaged suspended-sediment samples on four days using the equal-discharge-increment methodology described by Edwards and Glysson (1988). Bed material was sampled at as many as five equally spaced locations across the channel daily using a BM-54 sampler. At the eddy site, suspended-sediment samples were collected using a D-74 depth-integrating sampler deployed from a boat at four locations spanning the width of the eddy; each of the points was sampled twice daily during the flood. Concentrations of suspended sediment were determined using standard U.S. Geological Survey techniques (Guy, 1969). Grain-size distributions of the suspended sand were measured at 1/4  $\phi$  intervals using a visual-accumulation tube, and grain-size distributions of the bed material were measured at 1/2  $\phi$  intervals using dry sieving.

During the seven-day flood, total sediment concentrations determined by averaging depth-integrated samples from the main channel site decreased by approximately a factor of two, beginning with an average concentration of 0.15% by volume measured on March 27, 1996, and decreasing to a value of about 0.068% on April 2, 1996 (Fig. 3). This was a decrease of almost a factor of five in silt and clay concentration (from 0.035% to 0.008% by volume) and a decrease of slightly less than a factor of two in

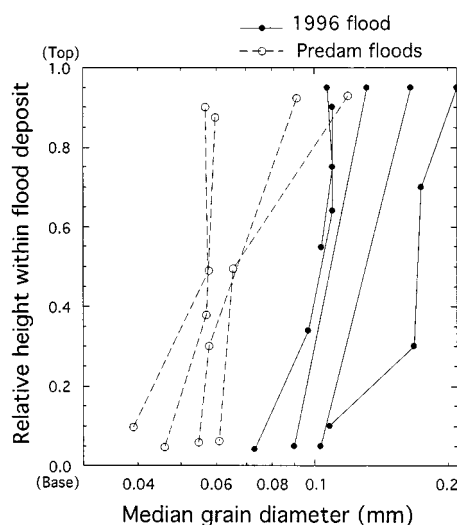
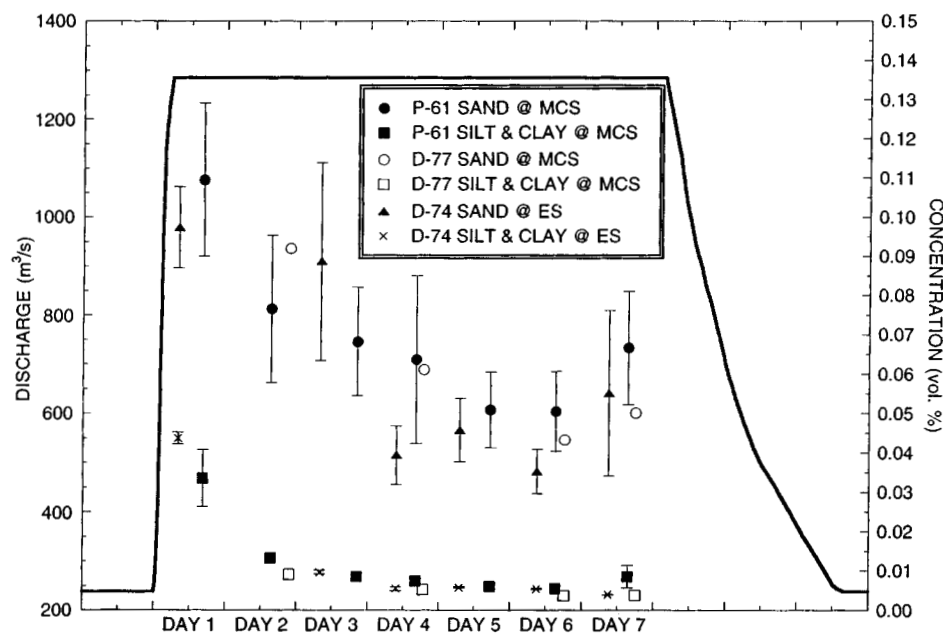


Figure 2. Plot of median grain size as function of relative height within flood deposits (1996 flood deposit at five sites and four predam flood deposits). Grain size nearly doubled during each flood.



**Figure 3.** Hydrograph of 1996 flood experiment and spatially averaged, depth-integrated sand and silt-plus-clay concentrations measured at main-channel and eddy sites. Error bars are one standard deviation. Travel time of flood between main-channel and eddy sites has been removed, so that beginning of day one at each site corresponds to time of first arrival of flood wave.

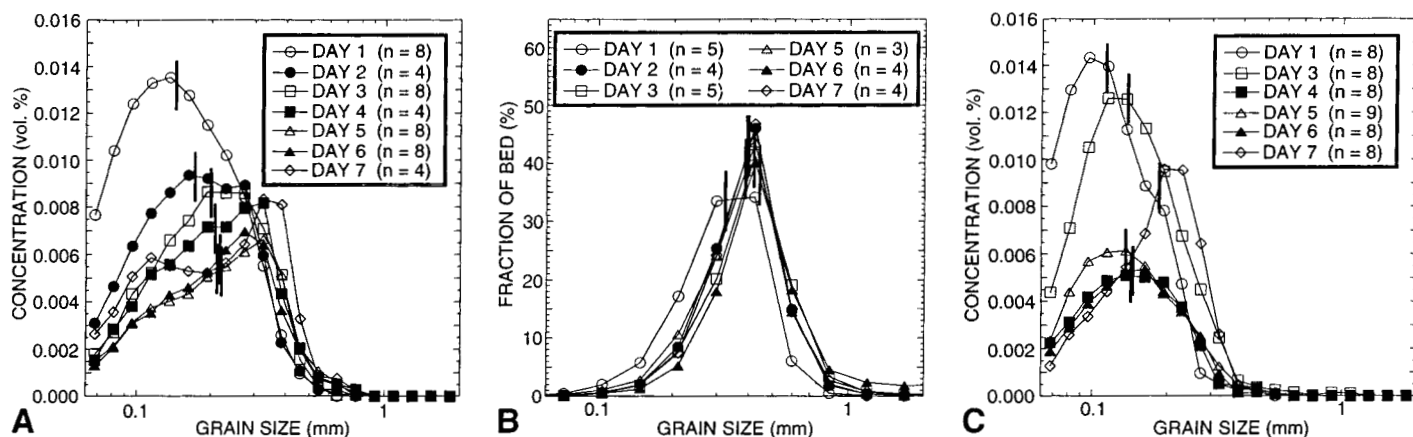
sand concentration (from 0.11 to 0.06% by volume). Sand was always the dominant portion of the suspended load, varying from 73% of the total suspended sediment on March 27, 1996, to 88% on the last day of high flow (April 2, 1996). Notably, total sediment concentration decreased the most during the first day or two of the flood, and continued to decrease at a lower rate until the last day of the flood, when it appears to have increased slightly, although the increase was within the range of measured variability. Remarkably similar results are found when spatially averaging the measurements taken in the eddy (Fig. 3). Despite the fact that flows in eddies are typically much lower in velocity than main-channel flows, total concentrations as well as the relative pro-

portion of sand are similar to those in the main channel 150 km upstream, with greatest similarity near the channelward margin of the eddy. Observations of sediment concentration and grain size at National Canyon (about 71 km downstream of the eddy site) are also similar to both the main-channel measurements at Phantom Ranch and the eddy measurements, suggesting that there was little longitudinal variation over this 220 km section of river.

At a river discharge of 1290 m<sup>3</sup>/s (45 400 cfs), particles finer than about 0.3 mm (by far the majority of measured suspended sediment during the flood) are carried predominantly in suspension. Similarity of measured suspended-sediment concentrations at the main channel and eddy sites

illustrates that eddy suspended-sediment concentration is largely controlled by the main-channel suspended-sediment concentration; the decrease in concentration during the seven-day experimental flood documents the supply-limited nature of sediment transport in the Colorado River in Grand Canyon.

The key to understanding the coarsening-upward sequences formed during the 1996 flood is found in the grain-size distribution of suspended sediment and bed material measured in the main channel and the grain-size distribution of suspended sediment measured within the eddy. During the flood, suspended sediment and bed material in the main channel evolved simultaneously; the median grain size of the suspended sediment and bed material increased from 0.14 to 0.21 mm and 0.3 to 0.4 mm, respectively, as shown in Figure 4 (A and B). In the main channel, bed material coarsened solely by depletion of the fines, whereas suspended sediment coarsened by depletion of fines as well as an increase in concentration of coarser sand. This same pattern was reflected by measurements in the eddy, where the suspended sediment coarsened during the flood, rapidly on the first few days of the flood and more slowly thereafter, beginning at a value of 0.11 mm and increasing to 0.19 mm on the final day of high flow (Fig. 4C). This increase in grain size occurred despite decreasing velocities in the eddy as deposition occurred. Furthermore, as in the main channel, the observed coarsening cannot be explained purely by a decrease in the quantity of fine material in suspension; the concentration of relatively coarse material increased in an absolute sense even while total concentration decreased (Fig. 4, A and C). Although the measurements within the eddy showed a slight tendency for grain size to decrease away from the main channel (shoreward), similarities in size distributions at different locations are more striking than differences, demonstrating the link-



**Figure 4.** Daily mean concentrations by size fraction of (A) suspended sand depicted in Figure 3 measured with P-61 sampler at the main-channel site; (B) bed measured with BM-54 sampler at main-channel site; and (C) suspended sand depicted in Figure 3 measured with D-74 sampler at eddy site. Number of samples in each spatially averaged measurement is indicated by *n* in legend. Heavy vertical lines indicate median grain sizes for each day.



age between the size distribution of suspended sediment in the eddy and main channel.

## DISCUSSION AND CONCLUSIONS

Inverse grading of flood deposits has been described by Osterkamp and Costa (1987) and studied by Iseya (1989), who attributed formation of inversely graded beds to changing sediment supply during floods in Japanese rivers. Iseya found that basal muddy deposits formed during the beginning of a flood, when the concentration of silt and clay was high. These deposits were overlain by inversely graded sands that also formed early during a flood (while discharge was still increasing). Iseya proposed that the increase in grain size during the flood was caused by a decrease in concentration of fine suspended sediment, in addition to an increase in flow intensity over the flood plain. As in the Japanese rivers, deposits of the 1996 flood in Grand Canyon exhibit upward coarsening and at some sites exhibit replacement of ripples by dunes; we hypothesize that the cause of both changes was depletion of fines on the bed in the main channel.

As fines were winnowed from the bed, the bed sediment coarsened, which caused the mean size of sediment supplied to the channel, eddies, and channel-margin deposits to coarsen. In the main channel, the coupling between the coarsening of the bed sediment and suspended sediment can be explained mechanistically in the following manner. For a sandy bed, the overall concentration of suspended sediment near the bed scales approximately with the shear stress in excess of the critical value for initiation of motion for the median grain size of the bed material, whereas the concentration of each size fraction scales approximately linearly with the fraction of that size class in the bed material (e.g., Smith and McLean 1977; McLean, 1992; Topping, 1997). Thus, the near-bed overall concentration of suspended sediment will decrease slightly as the median grain size increases from 0.3 mm to 0.4 mm, but the concentration of the coarser fractions will increase as a result of higher representation in the bed material, as shown in Figure 4 (A and B). In other words, as finer materials are winnowed from the bed, the median size in the bed coarsens slightly and the total concentration in suspension drops, but the concentrations of the coarsest fractions in suspension actually increase as they become more common in the bed. Although our observations can be explained solely in terms of the winnowing process described above, we can not rule out the possibility that upward-coarsening may have been enhanced by other processes—e.g., grain-size segregation by differing transport rates (Hand, 1997) into the eddies, or by excavation of coarser grains from underlying deposits.

The locally observed change from ripples to dunes (a depositional sequence of climbing ripples overlain by crossbedding) was caused by the increase in mean grain size of sediment supplied to the eddies. The conditions causing this change can be envisioned as a line representing a constant velocity and an increasing grain size on a plot showing bed phase as a function of grain size and velocity (Southard, 1971; Rubin and McCulloch, 1980; Southard and Boguchwal, 1990). In the rock record, observations of upward coarsening and change in bed configuration from ripples to dunes are typically interpreted to indicate stronger flows, but this is not necessarily the case. In the 1996 flood, peak discharge was held constant; coarsening of the bed caused the change in bed configuration.

Our observations indicate that limitations in sediment supply can drive changes in main-channel concentration and grain size, and thereby play a dominant role in the formation and stratigraphy of eddy deposits. Accordingly, dam-release scenarios for the purpose of sand-bar maintenance must consider the effect of decreasing main-channel concentrations on deposition rates in eddies and on transport of sediment through the canyon. The rate of decrease of main-channel concentration and the associated grain-size evolution during a given flood will depend on the timing of previous high flows and tributary inputs of sediment; this complexity mandates further investigation and monitoring of tributary inputs and subsequent main-channel transport as a function of grain size. It may be possible to exploit the bed-coarsening process and to manipulate dam releases in such a way as to maximize transport into eddies, while minimizing sediment transport out of the canyon. Although the dam enhanced the degree of supply limitation, grain-size evolution is a natural process that also occurred during predam floods.

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